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Bit Error Characteristics of Passive Phase Conjugation Underwater Acoustic Communication Due to a Drifting Source

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Abstract

Experimental work in underwater acoustic communications using passive phase conjugation has shown that the demodulation error depends on the relative drift rate between the source and receiver [Rouseff et al., IEEE J. Oceanic Eng. 26, 821-831 (2001)]. The observed effect involves the mismatch between the initial impulse response and the subsequent response after the source or receiver has changed locations. In the present work, the effect of drifting source is analyzed by numerical simulations and compared to the experimental results. The communications bit error rate is qualified as a function of drift rate, drifting direction, and source-receiver range.

Keywords: *Underwater Acoustic Communication, Passive Phase Conjugation, Inter-Symbol Interference, Bit Error Rate, Multipath Fading*

I. Introduction

A new method of coherent underwater acoustic communication system has been proposed[1]. It reduces efficiently the ISI (Inter Symbol Interference) due to the multipath fading if the temporal or spatial variation of channel is not severe. It is called as the passive phase conjugation (PPC) underwater acoustic communication since a demodulation of a digitally modulated data stream signal adopts the PPC process in which the probe signal is used on behalf of the time-reversal propagation. The passive phase-conjugate process on underwater communication, which mimics the matched signal processing, and its compensation mechanism of the multipath propagation had been studied originally by Dowling[2].

However, the proposed method has limited performance due to the underwater acoustic channel physics which includes background noise, time and spatial-varying fluctuation between source and receiver, and source/receiver motion. Resulting natures in communication are expressed as time spread and Doppler spread. The general intitutive characteristics of the channel physics is well explained in the underwater acoustic communication review article[3] and the diversity technique in underwater communication is proposed[3-5].

The diversity processing based on PPC technique in this study, is based on the matched signal processing by the ocean. The Parvulescu presented extensive and qualitative results about the matched signal processing by the ocean[6]. He had shown that its temporal stability is not as severe as its spatial stability and the spatial stability depends on both the horizontal and the vertical displacement. His study is based on the signal of a 400Hz bandwidth centred at 600Hz which is far less than that of the underwater acoustic communication in which the carrier frequency is order of several to tens KHz.

Other experimental work of matched signal processing was conducted to examine the temporal and spatial stability of a

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time-reversal mirror (or phase conjugate array process)[7-8]. The array span with respect to the water column and the spatial and temporal side lobe natures are addressed. Temporal changes in the medium due to surface waves and internal waves does not degrade much the focus if the average Green's function is not severely reduced by these time variations. However, the spatial displacement of source-receiver range induces more effect on vertical focal region.

In this study, the effect on the bit error due to relative drift between source and receiver is studied by numerical simulations. The mismatch between the initial probe response and the subsequent response after the source or receiver displacement is evaluated by the coherence of the matched signal of the probe response and the coherence is functioned to the bit error.

II. Theory

Fig. 1 shows the experimental geometry to address the bit error characteristics due to a drifting source in PPC process underwater acoustic communication. The source transmits information to the distant receiver array. The procedure starts by sending a short probe pulse which is one of the basis signal of the digitally modulated signal and waits for the channel to be clear of multipath arrivals, and then sends the signals corresponding to the data stream[1]. The source is assumed to approach to the receive array during the data transmission due to the current, wind or platform's moving. Therefore, the PPC processing using the initial probe pulse response has the mismatch effect on the coherent sum of the PPC process which gives the coherence degrade and corresponding temporal main lobe decrease. Doppler spread can also be included since the relative motion between the source and the receive array. We ignore the Doppler spread since we assigned the relative motion to be the slow fading by considering the baseband signal bandwidth is much greater than the Doppler spread. In order word, the channel of our interest is a frequency selective slow fading in which the coherence bandwidth due to the multipath is narrower than the baseband signal bandwidth.

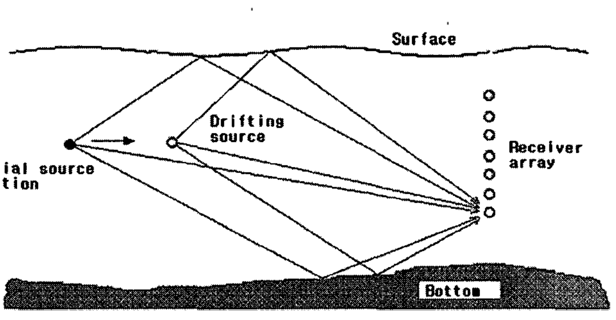

Fig. 1. Experimental configuration for source drifting effect on PPC process underwater communication.

In order to figure out this nature of the coherence degrade due to the source motion, and its effect on BPSK(Binary Phase Shift Keying) communication, we first consider the basis signal of the digitally modulated signa l $p(t)$ as the probe signal. It is given as

$$p(t) = \cos(2\pi f_c t)(1-\cos(2\pi t/T_b)),\ 0 \le t \le T_b \tag{1}$$

where f_c and T_b are carrier frequency and bit interval respectively. Considering only discrete multipath, the channel impulse response of ith receiver element is given as

$$h_i(t) = \sum_{k=1}^{K} \alpha_{ik}\delta(t-\tau_{ik}) \tag{2}$$

where, α_{ik} is the amplitude of the received signal of the kth path normalized by the amplitude of the direct path signal(k=1) and τ_{ik} is the difference in time of arrival between the direct path signal and reflected path signal. Therefore, the probe response signal $r_{p_i}(t)$ at ith receiver element is given as

$$r_{p_i}(t) = p(t) * h_i(t) = \sum_{k=1}^{K} \alpha_{ik} p(t-\tau_{ik}) \tag{3}$$

(3) shows the multiple probe signals weighted by the α_{ik}. Output of probe signal PPC process or autocorrelation of probe response signal is given as

$$\begin{aligned} y_i(t) &= r_{p_i}(t) * r_{p_i}(-t) = \{p(t) * p(-t)\} * \{h_i(t) * h_i(-t)\} \\ &= \sum_{k=1}^{K} (\alpha_{ik})^2 R_{pp}(t) + \sum_{\substack{k_1=1 \\ k_1 = k_2}}^{K} \sum_{k_2=1}^{K} \alpha_{ik_1}\alpha_{ik_2} R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}) \end{aligned} \tag{4}$$

where $R_{pp}(t)$ is autocorrelation of the probe signal and $(\tau_{ik_1}-\tau_{ik_2})$ is time difference between two different path signals. The first term of bracket is the sum of the multipath amplitude squares defined as main lobe amplitude and the second term is a group of cross product of two different multipaths amplitude defined as side lobe. It has been known that the random distribution of multipath which means different time values of each ($\tau_{ik_1}-\tau_{ik_2}$), guarantees the smaller side lobes than the main lobe. If each $|\tau_{ik_1}-\tau_{ik_2}|$ is larger than the T_b then the channel will be frequency selective fading. In order word, the channel delay spread is quite larger than the signal interval. If the channel is very much irregular in channel physics, then we obtain a large main lobe to side lobe ratio. In order to increase the main lobe under limited number of multipaths, we use the all M array elements signals to get spatial diversity gain. The sum of all M PPC processes is given as

$$y(t)=\sum_{i=1}^{M}y_i(t)=\sum_{i=1}^{M} r_{p_i}(t)*r_{p_i}(-t)$$
$$=\sum_{i=1}^{M}\sum_{k=1}^{K}(\alpha_{ik})^2R_{pp}(t)+\sum_{i=1}^{M}\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}) \tag{5}$$

If receiver array element multpath distribution is independent of each order then we obtain gain of M.

This is summary of existing PPC process considering the fixed source and fixed receiver in their position with the negligible temporal variation of channel impulse response. Considering source moving from its initial position, the PPC process or the cross correlation of the initial probe response and its matched signal version of displaced source position probe response at ith receiver is given as

$$y_i'(t)=r_{p_i}(t)*r_{p_i}'(-t)=\{p(t)*p(-t)\}*\{h_i(t)*h_i'(-t)\}$$
$$=\sum_{k=1}^{K}(\alpha_{ik}\alpha_{ik}')R_{pp}(t+\tau_{ik}-\tau_{ik}')+\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}'R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}') \tag{6}$$

where the prime denotes the matched signal version of the displaced source position. As shown (6), the main lobe is widen and its amplitude shows destructive or constructive interference but is always less than that of initial position since ($\tau_{ik}-\tau_{ik}'$) is not equal to zero. The sum of all M array elements crosscorrelation is given as

$$y'(t)=\sum_{i=1}^{M} r_{p_i}(t)*r_{p_i}'(-t)$$
$$=\sum_{i=1}^{M}\sum_{k=1}^{K}(\alpha_{ik}\alpha_{ik}')\ R_{pp}(t+\tau_{ik}-\tau_{ik}')+\sum_{i=1}^{M}\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}'R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}') \tag{7}$$

Therefore, if each element multpath distribution is independent of each order the smeared main lobe amplitude is still increased by M.

We apply (1)-(7) to the BPSK information sequence signal which is given as

$$I(t)=\sum_n I_n p(t-nT_b), \quad I_n=+1 \text{ or } -1 \tag{8}$$

Therefore the received signal of information sequence signal at ith receiver element is

$$I_i(t)=I(t)*h_i(t)=(\sum_n I_n p(t-nT)*h_i(t) \tag{9}$$

and we apply the PPC process using the probe response signal $p(t)*h_i(t)$ then

$$Iy_i(t)=(\sum_n I_n p(t-nT)*h_i(t)*p(-t)*h_i(-t)$$
$$=\{\sum_n I_n\sum_{k=1}^{K}(\alpha_{ik})^2R_{pp}(t-nT_b)+\sum_n\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}-nT_b)\} \tag{10}$$

Likewise, the sum of all output of information sequence signal PPC process or autocorrelation of information sequence signal is given as

$$Iy(t)=\sum_{i=1}^{M}Iy_i(t)$$
$$=\sum_{i=1}^{M}\sum_n I_n\sum_{k=1}^{K}(\alpha_{ik})^2R_{pp}(t-nT_b)$$
$$+\sum_{i=1}^{M}\sum_n\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}-nT_b) \tag{11}$$

As shown in (10)-(11), the second term in each equation shows ISI since after and before side lobes of other information sequence signals are summed in present information signal's main lobe. As mentioned, if side lobes are distributed randomly, their effect on ISI will be small. Finally, the sum of all M array elements cross correlation of source moving case is given as

$$Iy'(t)=\sum_{i=1}^{M}\sum_n I_n\sum_{k=1}^{K}(\alpha_{ik}\alpha_{ik}')R_{pp}(t+\tau_{ik}-\tau_{ik}'-nT_b)$$
$$+\sum_{i=1}^{M}\sum_n\sum_{\substack{k_1=1\\k_1\neq k_2}}^{K}\sum_{k_2=1}^{K}\alpha_{ik_1}\alpha_{ik_2}'R_{pp}(t+\tau_{ik_1}-\tau_{ik_2}'-nT_b) \tag{12}$$

In (12) for the moving source, the main lobe of present information signal will be widen in time scale and show destructive or constructive interference but its magnitude will be always less than that of initial position since ($\tau_{ik}-\tau_{ik}'$) is not equal to zero. In the correlation demodulation scheme, the one bit interval of PPC process signal $I_y(t)$(or $I_y'(t)$) is correlated with probe signal and this gives the Euclidean distance $d^{(e)}$ between the information sequence +1 and -1 as

$$d^{(e)} = \{2E(1-\rho_{I_y,p})\}^{1/2} \tag{13}$$

where E denotes the energy of one bit information signal. The correlation coefficient $\rho_{I_y,p}$ between $I_y(t)$ and $p(t)$ in one bit interval is defined as The $\rho_{I_y,p}$ is

$$\rho_{I_y,p} = \frac{1}{\sqrt{E_{I_y}E_p}}\int_0^{T_b} I_y(t)p(t)dt \tag{14}$$

where, E_{I_y} and E_p denote the energy of $I_y(t)$ and $p(t)$ and since $I_y(t)$ (or $I_y'(t)$) is always been distorted by side lobe signals, therefore $|\rho_{I_y,p}|$ is less than 1 so that $d^{(e)}$ is decreased in signal space. Therefore the bit error increases under additive white gaussian noise channel. In next section, bit error characteristics for moving source which is based on the correlation coefficient analysis, will be given.

III. Experimental results

Examination of bit error characteristics due to a drifting source was simulated numerically considering the PPC process communication experiment in the Puget Sound near Seattle May 8-12, 2000. The water depth, receiver array length, array element spacing, source-receiver horizontal range and bottom topography are not exactly same as with real experimental condition. The carrier frequency and the transmission rate are also changed but are same order as real experimental condition.

3.1. Environmental conditions in PPC process underwater communication

The water depth is assumed to be as 40-60m and surface and bottom reflection coefficient are assumed to be -0.8 and 0.6, respectively. The number of receiver array elements and element spacing in numerical simulation, are 7 and 4m, respectively which gives the same size of array length but twice in element spacing to the sea trial receiver array. We used 14 receiver elements and 2m spacing in the sea trial.

The number of reflection paths are assumed to be seven including direct path even if there are more than 10 discrete multipaths in sea trial as shown in Fig. 2. The measured and the simulated probe responses are shown by the order of corresponding array element. Both are not exactly coincident since the bathymetry and the channel physics are not same but the overall characteristic with discrete multipaths agrees well each other.

Fig. 3 shows one of the sea trial demodulation results and the simulation result to confirm the performance of PPC process underwater communication under without source drifting. The sea trial demodulation result is obtained for a varying bathymetry with an average depth of about 40m and the simulation result for a constant depth of 40m. Source/receiver range and SNR are the same as 1600m and 8.1dB for both cases. A mark '*' corresponds to a transmitted 'one' while a positive mark '+' to a transmitted 'zero'. Successful communication is possible and the variances of both cases are consistent with each other.

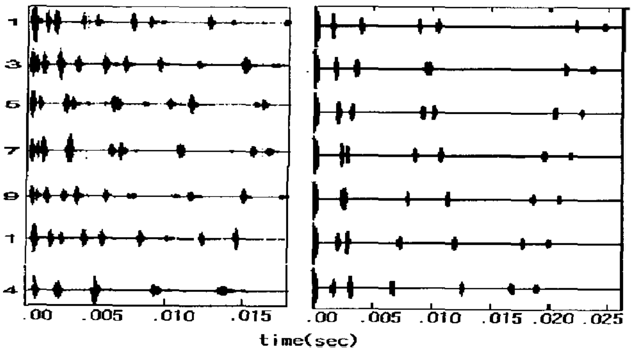

Fig. 2. Probe signal response along each element in receiver array. Right side shows that of the simulation result corresponding to the sea trial.

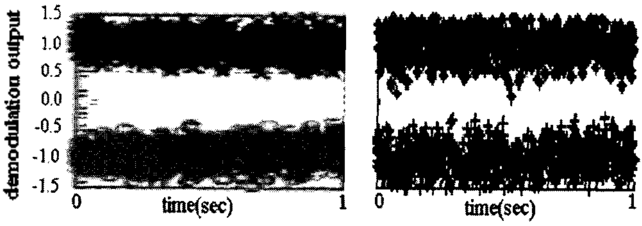

Fig. 3. Performance of the PPC process underwater communication. Sea trial and simulation results are well agreed with each other and show successful communication.

3.2. Bit error characteristics due to a drifting source

Fig. 4 shows one of the demodulation results for drifting source in sea trial. The water depth and the initial source/receiver range were 60m and 1500m, respectively and SNR was 11.8dB. As time elapsed, distance between +1 and -1 is decreased, so that information signal will be more susceptible to the background noise.

We analyzed this phenomenon by correlation coefficient between the PPC process signal of probe response at initial source position, (5) and that at moved source position, (7). The decrease of this correlation coefficient will give a smaller main lobe in information signal resulting smaller Euclidean distance $d^{(e)}$ in (14). Fig. 5 shows the correlation coefficient with respect to drifting distance for two different given initial source/receiver ranges. At short source/receiver range, the correlation changes more rapidly than at long range and induces more rapid variation of correlation.

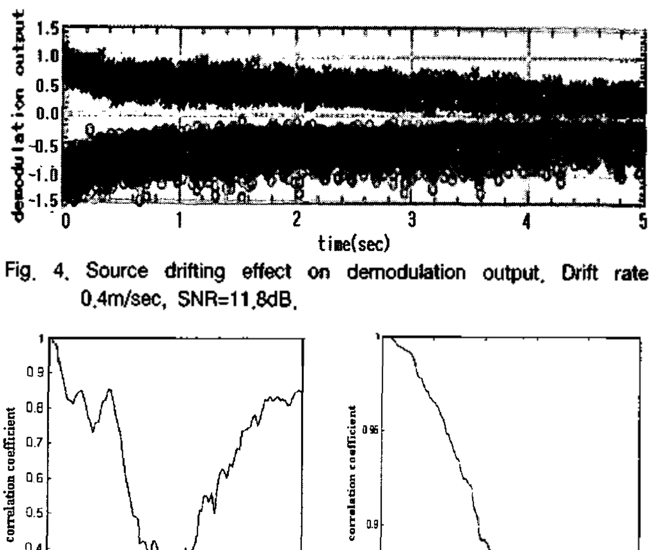

Fig. 4. Source drifting effect on demodulation output. Drift rate 0.4m/sec, SNR=11.8dB.

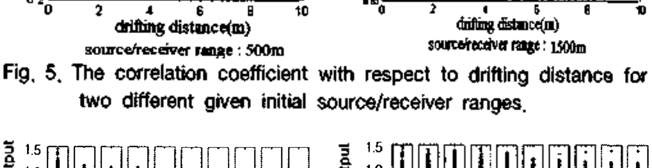

Fig. 5. The correlation coefficient with respect to drifting distance for two different given initial source/receiver ranges.

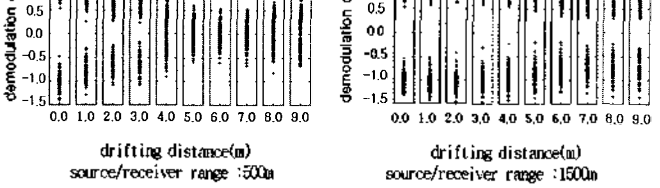

Fig. 6. Bit error characteristics corresponding to Fig. 5 for source drifting.

Fig. 6 is the corresponding bit error characteristics. Demodulation output is analysed in 1m range step with 200 information data signal. As shown, correlation degrade matches with the demodulation output characteristics i.e. the bit error nature.

Comparing Fig. 5 to Fig. 6, Correlation agrees well with the bit error characteristics. Exact degrde rate can be obtained by assessing the Euclidean distance $d^{(e)}$ substituting the correlation coefficients in Fig. 5 to (13). For reference, 0.7 of correlation coefficient gives about one half of Euclidean distance $d^{(e)}$. The sea trial result of Fig. 4 corresponds to right hand side in Fig. 6. Both agrees well each other in general trend such that the demodulation output is degraded with drifting distance increase. However, demodulation output of the sea trial is worse than that of the simulation. This may be due to the drifting rate error, source/receiver positioning error or source displacement in vertical direction. It has been known that the spatial displacement of source-receiver range induces more effect on vertical focal region[7-8].

IV. Conclusions

A qualitative description of the effect of drifting source on PPC process BPSK underwater acoustic communication has been presented. The bit error rate is qualified as a function of drift rate and source-receiver range. We analyzed the bit error by correlation coefficient between the PPC process signal of probe response at initial source position and that at moved source position. The increase of source drifting distance induces the decrease of the correlation coefficient and results in smaller Euclidean distance in demodulation signal space. The correlation degrade by source drifting agrees well with the bit error rate and the distant source/receiver range gives slower change of bit error variation than short source/receiver range with the same source drifting rate.

The sea trial and simulation results agree well each other in general trend such that the demodulation output is degraded with drifting distance increase. However, demodulation output of the sea trial is worse than that of the simulation due to the drifting rate error or source/receiver positioning error.

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References

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1. D. Rouseff, D. R. Jackson, W. L. J. Fox, C. D. Jones, J. A. Ritcey, and D. R. Dowling, "Underwater Acoustic Communication by Passive-Phase Conjugation : Theory and Experimental Results," IEEE J. Oceanic Eng., 26 (4), 821-831, 2001.
2. D. R. Dowling, "Acoustic pulse compression using passive phase-conjugate processing," J. Acoust. Soc. Am., 95 (3), 1450-1458, 1994.
3. D. B. Kilfoyle, and A. B. Baggeroer, "The State of the Art in Underwater Acoustic Telemetry," IEEE J. Oceanic Eng., 25 (1), 4-27, 2000.
4. J. A. Catipovic, L. E. Freitag, "Spatial Diversity Processing For Underwater Acoustic Telemetry," IEEE J. Oceanic Eng., 16 (1), 86-97, 1991.
5. Q. Wen, J. A. Ritcey, "Spatial Diversity Equalization Applied to Underwater Communications," IEEE J. Oceanic Eng., 19 (2), 227-241, 1994.
6. A. Parvulescu, "Matched-signal("MESS") processing by the ocean," J. Acoust. Soc. Am., 98 (2), 943-960, 1995.
7. W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla, and D. R. Jackson, "Phase conjugation in the ocean : Experimental demonstration of an acoustic time-reversal mirror," J. Acoust. Soc. Am., 103 (1), 25-40, 1998.
8. W. S. Hodgkiss, H. C. Song, W. A. Kuperman, T. Akal, C. Ferla, and D. R. Jackson, "A long-range and variable focus phase-conjugation experiment in shallow water," J. Acoust. Soc. Am., 105 (3), 1597-1604, 1999.

[Profile]

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